The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians

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Summary of the Problem

The mountainous terrain of the southern Appalachians is quite vulnerable to flash flooding due to their steep slopes and narrow basins. Each year, flooding and flash flooding is one of the leading causes of weather fatalities and damage in the region. Forecasters need a thorough understanding of the meteorological factors that produce heavy rainfall events. The overall objective of this project is to improve our understanding of the meteorological factors that produce flooding by investigating the influence of Atmospheric Rivers (ARs) on extreme precipitation. The improved understanding of ARs will increase the accuracy of both the flash watch and warning program, thus saving lives and protecting infrastructure.

Located just west of the southern Appalachian Mountains, the Knoxville, Tennessee metropolitan area (U.S. Census 2013 estimated population of 850,000+) relies partly on precipitation falling in the mountains to supply water via the French Broad, Pigeon, Little Pigeon, Little River, and Doe Rivers (Figure 1). However, an overabundance of rainfall in the mountains produces significant challenges for those living in and near the southern Appalachians.

Most studies examining precipitation relevant to Knoxville and the eastern Tennessee Valley have undertaken a broad regional view by examining synoptic scale weather patterns contributing to heavy rainfall events in the southeastern United States (Moore et al. 2015, Rickenbach et al. 2015, Stevenson and Schumacher 2014, Parker and Ahijevych 2007, Carbone et al. 2002, Hansen et al. 1998, Geerts 1998, Konrad 1997). Few studies (Duan et al. 2015, Kelly et al. 2012, Gaffin and Hotz 2000) focus on a climatology of precipitation production within the sub-region of the southern Appalachian Mountains. A challenge of evaluating precipitation in the mountains is the accuracy of operational gridded quantitative precipitation estimate data sets (Tao and Barros 2013) for a region having known challenges with remotely-sensed observations of rainfall (Duan et al. 2015). Direct observations of rainfall in the mountains (e.g., COOP and CoCoRaHS) are typically at easy access, low elevation locations that can miss important and significant precipitation production at high elevations.

Much research (Lavers and Villarini 2015, Moore et al. 2012, Neiman et al 2008, Ralph et al. 2004) recently has been devoted to the impact of narrow lower-tropospheric air streams having high amounts of integrated water vapor, ARs, (Zhu and Newell 1998) on precipitation events in the United States. Some studies (Lavers and Villarini 2015, Neiman et al. 2008) indicate the contribution of ARs to heavy precipitation and flooding events is greatest during the winter, when poleward vapor fluxes are large due to strong winds at low levels, associated with the pre-cold frontal jet. In contrast, the analysis of a flooding case study event in May 2010 in Nashville, TN (Moore et al. 2012) shows an AR contribution during the warm season, when the large-scale weather pattern is stalled and moist low-level flow contributes to an increase in CAPE that feeds slow-moving MCSs.

The AR climatology presented in Lavers and Villarini (2015) suggests that precipitation of the Appalachian Mountains is minimally influenced by ARs, compared to regions immediately upstream and downstream of the mountains. An outcome of the proposed study will be to test if this result is robust, supported by true atmospheric processes, or if it is an artifact of the difficulty in estimating precipitation in remote locations of the mountains (Duan et al. 2015). If ARs indeed prove to be an important contributor to the production of precipitation in the southern Appalachian Mountains, they can provide a good warning flag to the operational forecaster as their spatial and temporal evolution occurs on scales large enough that they are detectable and predictable via current technological capabilities.

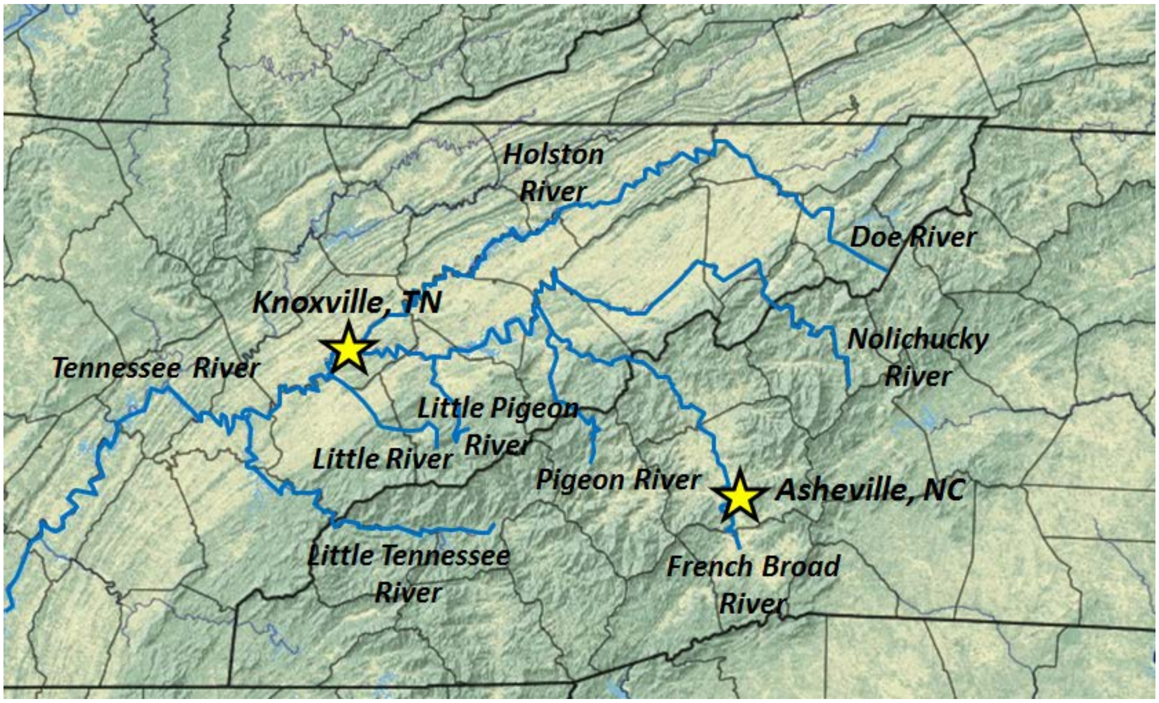

Figure 1. Area of interest of the proposed study. Topographic relief of the southern Appalachians (shading) and main stream rivers spilling into the Tennessee Valley (blue).

Statement of Objectives

The proposed study will focus on the influence of ARs in the precipitation of the southern Appalachian Mountains, defined in this study, as the mountains located in eastern Tennessee and western North Carolina (Figure 1). Of particular interest will be to examine a five year climatology (1 July 2009 – 30 June 2014) of MODIS total precipitable water (TPW) observations, mid and high elevation rain gauge network (Duke/UNC Asheville [UNCA]/NASA) observations (Duan et al. 2015), USGS river and stream gauge observations, and gridded atmospheric data (e.g., GFS analyses) to determine the frequency of ARs impacting the southern Appalachians and the intensity of precipitation and severity of flooding that occurs during their interaction with the mountains [***Objective 1***]. If AR events are distributed above the upper-quartile of observed daily river and stream flow rates during the five year study period, individual case studies will be examined to analyze common and unique aspects of each to illuminate potential 'signals' that might be used by operational forecasters to issue flood warnings.

The five year climatology period is defined according to the availability of precipitation observations at mid and high elevation tipping bucket rain gauges in the Pigeon River Basin of western North Carolina and eastern Tennessee (Figure 2, [Figure 1 of Duan et al. 2015]). MODIS TPW observations will be examined over the five year study period in the eastern Gulf of Mexico and the southeastern U.S. coastal zone of the western Atlantic Ocean to determine median and upper-quartile ('humid') events. Gridded GFS atmospheric analysis fields will be used to calculate integrated vapor transport (IVT, Moore et al. 2012, Neiman et al. 2008) for humid events flagged by MODIS TPW observations. In order for a humid event to qualify as an AR, the IVT value must exceed [1] a threshold for a single snapshot in time (most likely in the synoptically-forced winter season) or [2] an integrated threshold over a period in time (most likely in the convectively-forced warm season).

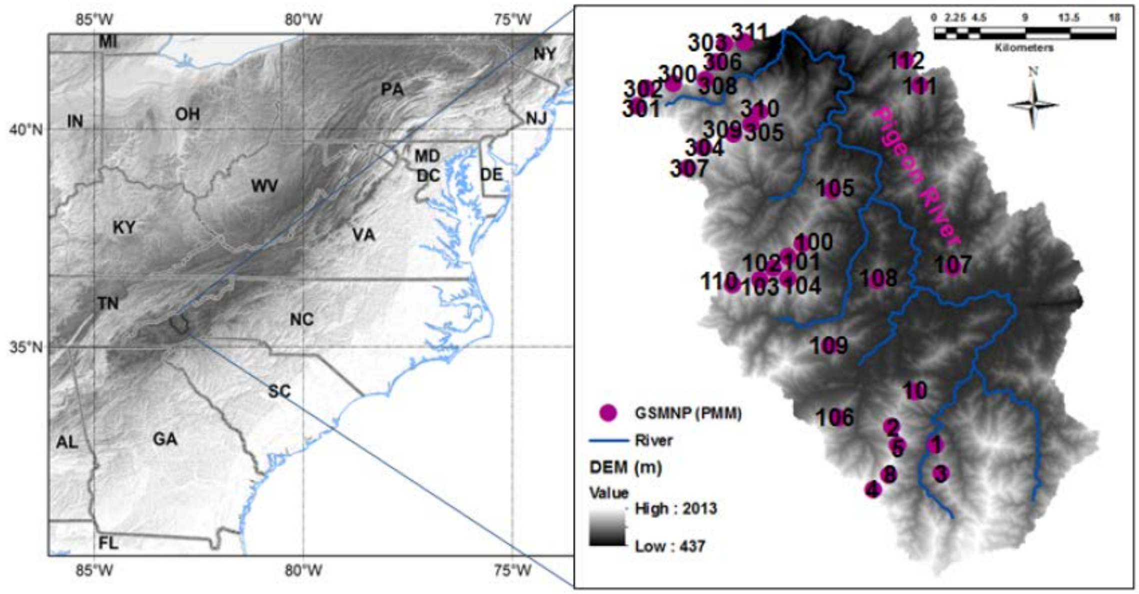

Figure 2. Figure 1 of Duan et al. 2015. Region of rain gauge network in the Pigeon River basin. Note RG0XX, RG1XX, and RG3XX were installed in summer 2007, 2008, and 2009, respectively.

The societal impact of AR events will be examined through the inspection of USGS river and stream gauge network data, seeking evidence of flooding, and by browsing Knoxville and eastern Tennessee Valley area observations contained in Storm Data reports to determine the severity of precipitation events associated with ARs. AR-influenced case studies having significant societal impacts will be collected and archived in order to develop a storm atlas [***Objective 2***]. These case studies will be carefully scrutinized to find commonalities and distinctions to assist forecasters in visualizing the degree of atmospheric variability associated with AR-influenced heavy rainfall events in the southern Appalachian Mountains.

Current methodologies used for predicting heavy rainfall events in the southern Appalachians by forecasters at the NWSFO of Morristown, TN, although robust, do not capture the potential of the more significant events due to a missing climatological context. For what threshold TPW and IVT values of AR events is destructive precipitation and flooding more likely? Are these threshold values more common under a particular type of synoptic or mesoscale weather regime? Does a particular weather pattern configuration lead to more efficient precipitation production over the southern Appalachian Mountains in the presence of an AR? We feel a better utilization of AR tools, especially those with a climatological context, will help diagnose flooding. Through a climatology-based understanding of AR events, we hope to more effectively diagnose the associated synoptic and/or mesoscale conditions favorable to maximizing the production of intense rainfall [***Objective 3***].

The study addresses the highest priority items for collaborative research, activities that:

- improve understanding of a local mesoscale forecasting problem,
- assist operational forecasters in enhancing their educational backgrounds,
- increase the university research community's awareness of operational problems and needs,

- create case studies or new data analysis techniques with wide application and usefulness in teaching, research, or operational forecasting, and

- bring together students, operational forecasters, educators, and regional or local experts in forums designed to share information.

Along with addressing NWS collaborative research priority items, the study will also serve to improve the quality of education for the undergraduate students enrolled at UNCA through the increased awareness of the NWS operational problems and needs and through the direct involvement of research in AR climatology development and case study analysis.

The proposed study will provide insights related to a high priority topic area of the NOAA/NESDIS GOES-R Program:

- integrating GOES-R products with other data, products and models

by examining the combined utility of MODIS TPW observations with IVT calculated from gridded GFS atmospheric analysis fields over the five year study period. Development of the combined MODIS TPW and GFS IVT AR-flagging methodology during the proposed one year project will allow a smooth transition to the application of GOES-R TPW observations at WFO MRX once the new satellite platform has been launched into space and made operational.

One of the benefits of NOAA's Weather-Ready Nation is a society that is able to prepare for and respond to environmental events that affect safety. The increased awareness and understanding of ARs, and their interaction with the terrain features of the southern Appalachians, will not only aid a forecaster's ability to predict and warn these events, but also increase their understanding of the effects of the main stream rivers spilling into the Tennessee Valley.

Specific Tasks to be Accomplished

The WFO MRX forecasters and investigators at the UNCA Atmospheric Sciences Department (ATMS) will collaborate by addressing the following unique and shared tasks needed to meet Objectives 1-3 of the proposed study,

<u>UNCA tasks during the study:</u>

- build algorithm for browsing MODIS TPW observations over the eastern Gulf of Mexico and southwestern Atlantic Ocean to establish a climatology of each of the four seasons (DJF, MAM, JJA, SON) over the five year study period,
- incorporate existing algorithms for calculating IVT from gridded GFS analyses (http://ssd.wrh.noaa.gov/naefs/?type=ivt) and determine if flagged 'humid' TPW events qualify as associated with an AR (http://www.esrl.noaa.gov/psd/psd2/coastal/satres/data/html/ar_detect_gfs.php), and
- examine precipitation output (mid and high elevation rain, river and stream gauge observations) to determine if AR events qualify as heavy rainfall events.

<u>WFO MRX tasks during the study:</u>

- examine reports (e.g., Storm Data) to determine if AR events qualify as disruptive and having a high societal impact and
- convert storm atlas datasets to the Weather Event Simulation (WES) infrastructure supported by AWIPS2, making case studies available for training in the WFO.

Shared tasks during the study:

- build storm atlas of heavy rainfall and disruptive events associated with ARs and
- determine common and unique patterns between AR case studies to streamline forecasting methodology.

Progress on the study tasks will be encouraged by having two face-to-face meetings and monthly conference calls for study team members to report on their status and to assist in completion of overlapping (shared) tasks. An undergraduate investigator under the supervision of PI Miller from UNCA will make a research presentation to the WFO MRX forecasters at the first in-person meeting in January 2016. A collaborative face-to-face meeting will take place at WFO MRX at the second in-person meeting in June 2016 to address common and unique aspects of each AR case study to illuminate potential 'signals' that might be used by operational forecasters to issue flood warnings. A goal will be to automate the detection of these signals by finding analogs of approaching weather scenarios in the new storm atlas via the operational Cooperative Institute for Precipitation Systems database (http://www.eas.slu.edu/CIPS/ANALOG/analog.php). Overall results of the study will be disseminated to colleagues in the field of meteorology through a conference presentation made in fall 2016 and through a manuscript submitted to a refereed scientific journal in calendar year 2017.

Time Schedule [delayed due to the updating of the proposal in late summer 2015]

1 September 2015 – first day of study

1 December 2015 – TPW and IVT climatology tasks completed at UNCA

20 January 2016 – research results presentation at WFO MRX (workshop)

20 May 2016 – case study storm atlas completed

20 June 2016 – streamlined forecast methodology collaborative workshop at WFO MRX

20 July 2016 – case study datasets converted into AWIPS2-compatible WES format

30 August 2016 – conference presentation completed - final day of study

Principal Investigators

Douglas K. Miller has been in his position as a Professor in the Atmospheric Sciences Department at UNCA since July 2004 where he focuses on teaching courses in mesoscale and synoptic scale meteorology and numerical weather prediction. His previous years were spent in a post-doctoral and research professor position at the Naval Postgraduate School studying coastal meteorology and flow interaction with coastal mountains. He received his M.S. in atmospheric sciences at the University of Washington in December 1990 and his Ph.D. in atmospheric sciences at Purdue University in July 1996.

David G. Hotz has been the Science and Operations Officer at WFO Morristown since June 2005. He began his NWS career at the Weather Service Office at Bristol, Tennessee in August 1986, and then transferred to the Agricultural Weather Service Center (AWSC) Stoneville, Mississippi as an Agricultural Forecaster in January 1988. In December 1990, he transferred to the National Weather Service Office at Amarillo, Texas as a Journeyman Forecaster, and then to the Weather Forecast Office at Morristown, Tennessee as a Senior Forecaster in September 1994. His interests include developing local computer applications, northwest flow snowfall, severe storms, and local climatological studies. He has a B.S. degree (1986) in Agricultural Meteorology from Purdue University.

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